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Confrontation of MOdified Newtonian Dynamics with the rotation curves of early-type disc galaxies

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ABSTRACT

We extend the MOdified Newtonian Dynamics (MOND) analysis to a sample of 17 high surface brightness, early-type disc galaxies with rotation curves derived from a combination of 21-cm H I line observations and optical spectroscopic data. A number of these galaxies have asymptotic rotation velocities between 250 and 350 km s^{-1} making them among the most massive systems (in terms of baryonic mass) considered in the context of MOND. We find that the general MOND prediction for such galaxies – a rotation curve which gradually declines to the asymptotic value – is confirmed, and in most cases the MOND rotation curve, determined from the mean radial light and gas distribution, agrees in detail with the observed rotation curve. In the few cases where MOND appears not to work well, the discrepancies can generally be understood in terms of various observational errors – such as incorrect orientation angles and/or distances – or of unmodelled physical effects – such as non-circular motions.

The implied mass-to-light ratios for the stellar disc and bulge constrain the MOND interpolating function; the form recently suggested by Zhao & Famaey yields more sensible values than the one traditionally used in MOND determinations of galaxy rotation curves.

Key words: gravitation – galaxies: kinematics and dynamics – galaxies: structure – dark matter.

1 INTRODUCTION

As an acceleration-based modification of Newtonian dynamics, MOdified Newtonian Dynamics (MOND) makes general predictions about the contrasting form of rotation curves in low surface brightness (LSB) and high surface brightness (HSB) galaxies (Milgrom 1983). If surface density is roughly proportional to surface brightness, then LSB galaxies have low internal accelerations and MOND predicts a large discrepancy between the visible and Newtonian dynamical mass within the optical image; in particular, in these systems the rotation curves should slowly rise to the final asymptotic circular velocity. On the other hand, HSB galaxies, within the bright inner regions, are in the high acceleration, or Newtonian, regime. MOND predicts that there should be a small discrepancy between the observable mass and the dynamical mass within the bright optical image; moreover, the rotation curves should rapidly rise and then fall in an almost Keplerian fashion to the final asymptotic value. H I observations of several galaxies spanning a range of surface brightness certainly exhibit this general trend (Casertano & van Gorkom 1991) but the sample is small and the data are inhomogeneous.

With respect to LSB galaxies the MOND predictions have been spectacularly confirmed by H I observations of such objects over the past decade (McGaugh & de Blok 1998; Sanders & Verheijen 1998). Most recently, Milgrom & Sanders (2007) have extended this analysis to several galaxies with extremely low mass or rotation velocity – systems where the observed distribution of neutral gas dominates the detectable mass budget of the galaxies and the mass-to-light ratio (M/L) of the stellar component effectively disappears as a free fitting parameter. They demonstrated that MOND generally accounts for the form and the amplitude of rotation curves in these systems.

At the other extreme, there has not been much consideration of the high-luminosity or HSB galaxies. The gravitational force distribution probed by planetary nebulae kinematics in several elliptical galaxies (Romanowsky et al. 2003) is consistent with MOND (Milgrom & Sanders 2003) – primarily the basic prediction of a small discrepancy in HSB systems. However, because of the uncertain degree of anisotropy in the velocity distribution of these probes, rotation curves remain a far more unambiguous tracer of the radial dependence of force.

A sample of eight rapidly rotating, but late-type, disc galaxies has been presented by Spekkens & Giovanelli (2006), but these objects are apparently not as centrally concentrated or bulge-dominated as the early-type rapid rotators that we require in order to confront the

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generic MOND predictions. The rotation curves of several early-type disc galaxies in the published literature at the time were considered in terms of MOND by Sanders (1996), but the data were quite inhomogeneous and the derived rotation curves were not of the same quality as in more gas-rich systems. The basic problem is that high-luminosity, HSB galaxies tend to be of early-type (S0–Sb) and have generally low gas content with patchy distributions.

Recently, a more homogeneous sample of early-type disc galaxies with high-quality H I observations has become available (Noordermeer et al. 2005, hereafter N05). In Noordermeer et al. (2007, hereafter N07), these data were combined with high-resolution optical spectroscopic observations to derive rotation curves for 19 systems. These galaxies have morphological types ranging from S0 to Sab, and have, for the most part, an apparent spheroidal bulge component and a high central surface brightness. They are mostly massive systems, with maximum rotation velocities of 200–500 km s^{-1}. Significantly, surface photometry in the *B* and *R* bands exists for all these galaxies (Noordermeer & van der Hulst 2007); this is necessary to estimate the distribution of visible matter and the resulting Newtonian acceleration.

In this paper, we extend the MOND analysis to this sample of HSB, rapidly rotating galaxies. The rotation curves follow the general MOND predictions. In the bright inner regions there is little discrepancy between the observed and Newtonian rotation curves, while at larger radii the rotation curves often decline to an asymptotically constant value. Applying the MOND formula to the mass distribution as traced by the visible light and H I emission, we find that in most cases the observed rotation curve is well matched by the MOND prediction. There are a few exceptions where the observed rotation curves appear to deviate from the MOND predictions, and these cases are considered in more detail.

Because the accelerations range smoothly from the Newtonian to the MOND regime, this sample of rotation curves can be used to constrain the form of the MOND interpolating function μ. Using the typically applied form for this function we find that the M/L values of the bulge and disc are often implausible; in particular, in several cases a higher M/L is required for the disc than for the bulge. Using the simpler interpolating function recently suggested by Zhao & Famaey (2006), the M/L values become more reasonable with the disc values generally comparable to or lower than those of the bulge.

The remainder of this paper is structured as follows. In Section 2, we describe the sample of galaxies and the observational data. Section 3 describes the procedures we used to derive the predicted MOND rotation curves. In Section 4, we present the general results, while individual galaxies are discussed in Section 5. Finally, in Section 6, we draw some conclusions.

2 THE SAMPLE AND OBSERVATIONAL DATA

The rotation curves in N07 are based on the H I data from N05, which in turn were obtained in the framework of the Westerbork survey of H I in spiral and irregular galaxies (WHISP; Kamphuis, Sijbring & van Albada 1996; van der Hulst, van Albada & Sancisi 2001). A full description of the sample selection is given in N07; here we briefly mention a few points relevant for this study.

All galaxies in N07 have well-resolved H I velocity fields (at least 5–10 independent beams across), and sufficient H I across the disc to define a complete two-dimensional field. Moreover, their velocity fields show no obvious evidence for large-scale deviations from circular motions about the centre of the galaxy: no strongly interacting or strongly barred galaxies were selected to avoid complications introduced by non-circular motions. None the less, the sample is unavoidably less ideal for the purpose of testing MOND than are previous samples of later type galaxies (e.g. the Ursa Major sample of Sanders & Verheijen 1998). As discussed by N05, the surveyed galaxies were selected in part because they are more gas rich than the general population of early-type galaxies. They may have therefore acquired their gas from recent accretion events or minor mergers; the frequent occurrence of asymmetries and optical indications of interactions suggest that this may be the case. Even though strongly non-interacting galaxies have not been included in this subsample, the gas in these systems may not be entirely relaxed, and the value of gas kinematics as a tracer of the gravitational potential may be compromised. Therefore, the a priori expectation is that rotation curve fits would be generally inferior to that of earlier samples.

Of the 19 galaxies in N07, two have been dropped here. The first (UGC 624) has an asymmetric velocity field, undermining the quality of its rotation curve. A second (UGC 4605) is nearly edge-on and no photometry is available to trace the stellar mass distribution.

The observational properties of the remaining sample of 17 galaxies is given in Table 1. Note that all distances are estimated from the systemic velocity, corrected for Virgo-centric inflow and assuming $h = 0.75$.

For all of these objects, the H I velocity field has been supplemented by higher resolution single-slit optical spectra in the central regions. This is evident as a much higher density of data points defining the inner observed rotation curves. While higher resolution data are certainly desirable in the region where the rotation velocity is changing rapidly, a note of caution is necessary. These data points are based upon single-slit spectra and the implicit assumption is that the observed velocities along the slit can directly be translated into rotational velocities (using the position angle and inclination as defined by the H I velocity field). But streaming motions of gas, for example, by weak non-axisymmetric distortions in the central regions, can introduce uncertainties in the interpretation of optical velocities as circular velocities. Moreover, in any blind fitting procedure, the more numerous optical data points should not be given weight equal the outer H I points, to avoid that the fitted model is determined entirely by the optical data.

In addition to these considerations, there are the usual uncertainties which complicate the interpretation of the rotation curves as tracers of the radial force distribution. There are, in a number of cases, at least weak non-axisymmetric distortions (e.g. bars) in the inner region that introduce errors in the derived rotation curve. For other objects, the gas layer in the outer regions is clearly warped. In principle, these effects were taken into account as well as possible by using a tilted-ring model in the derivation of the rotation curves (Begeman 1987, 1989): a set of rings each with its own inclination, position angle and rotation velocity was fitted to the radial velocity data (see N07 for details). But this procedure contains implicit physical assumptions – such as constant azimuthal velocity in a ring – which may or may not be realistic. The overall consequence of these effects is that the presented rotation curves cannot with certainty be taken as a true indicator of the force. The indicated error bars are an attempt to quantify these uncertainties, but we cannot exclude the possibility that in individual cases, the true circular velocity deviates from the observed rotation curves.

Finally, we use the photometric data from Noordermeer & van der Hulst (2007) to derive the contribution to the gravitational field from the stars. Most of these galaxies show evidence for two distinct components in the light distribution – a central spheroidal bulge and a more extended disc component. Noordermeer & van der Hulst (2007) presented bulge–disc decompositions, where a bulge with a

Table 1. Sample galaxies: basic data. Column (1): UGC number; column (2): alternative name; column (3): morphological type; column (4): distance column (based on Hubble flow, corrected for Virgo-centric inflow and assuming $h = 0.75$; columns (5) and (6): B- and R-band luminosities (corrected for Galactic foreground extinction); column (7): central surface brightness (R band; corrected for Galactic foreground extinction); column (8): maximum and column (9): asymptotic rotation velocity and column (10): centripetal acceleration at last point in rotation curve. Column (3) was taken from NED, column (4) from N05 and columns (5)–(7) from Noordermeer & van der Hulst (2007).

UGC (1)	Alternative name (2)	Type (3)	D (Mpc) (4)	L_B (10^{10} L$_\odot$) (5)	L_R (10^{10} L$_\odot$) (6)	$\mu_{0,R}$ (mag arcsec^{-2}) (7)	$V_{\rm m}$ (km s^{-1}) (8)	$V_{\rm f}$ (km s^{-1}) (9)	$a_{\rm f}$ (10^{-8} cm s^{-2}) (10)
2487	NGC 1167	SA0-	67.4	8.79	10.47	17.00	390	320	0.46
2916	–	Sab	63.5	4.09	3.37	16.97	220	200	0.29
2953	IC 356	SA(s)ab pec	15.1	4.79	5.50	15.72	315	260	0.44
3205	–	Sab	48.7	3.53	2.99	17.17	240	210	0.40
3546	NGC 2273	SB(r)a	27.3	1.59	1.84	15.84	260	190	0.43
3580	–	SA(s)a pec:	19.2	0.328	0.311	17.87	127	120	0.20
3993	–	S0?	61.9	1.85	1.84	16.99	300	250	0.41
4458	NGC 2599	SAa	64.2	5.55	5.86	16.00	490	260	0.34
5253	NGC 2985	(R')SA(rs)ab	21.1	3.44	3.05	15.56	255	220	0.31
6786	NGC 3900	SA(r)0+	25.9	1.47[a]	1.50	15.88	230	210	0.48
6787	NGC 3898	SA(s)ab	18.9	1.56	1.72	15.35	270	250	0.64
8699	NGC 5289	(R)SABab:	36.7	0.964	1.05	16.47	205	180	0.45
9133	NGC 5533	SA(rs)ab	54.3	4.79	5.92	16.27	300	230	0.17
11670	NGC 7013	SA(r)0/a	12.7	0.745	0.879	15.59	190	160	0.40
11852	–	SBa?	80.0	2.33	2.17	17.50	220	160	0.09
11914	NGC 7217	(R)SA(r)ab	14.9	2.00	1.84	16.05	305	290	3.48
12043	NGC 7286	S0/a	15.4	0.160	0.107	18.71	93	85	0.18

[a]No B-band data available in Noordermeer & van der Hulst (2007); $L_{\rm B}$ taken from LEDA.

generalized Sérsic profile was subtracted from the total light distribution to give the remainder as the disc component. Assuming that the disc is a flat system, with a vertical scaleheight one-fifth of the radial scalelength, and comparing the ellipticity of the isophotes in the central bulge-dominated regions with those of the outer disc, they could also estimate the intrinsic axial ratio of the bulges. Note that the bulge–disc decomposition introduces additional uncertainty in our mass models. Usually, a range of bulge and disc parameters can be derived to fit the observed intensity distribution. We have verified that, as long as the bulge and disc M/L values are comparable, differences in the bulge–disc decompositions have little effect on the mass models. However, when the M/L values differ strongly, this is no longer the case, and errors in the decomposition propagate into the mass models.

3 PREDICTED MOND ROTATION CURVES

The procedure here for generating a MOND rotation curve is basically the same as described previously (e.g. Sanders & McGaugh 2002). One complication for this sample is the presence of a bulge which may have a different M/L than the disc component. This adds uncertainty due to the decomposition procedure as well as a second free parameter.

Basically one takes the photometry in each of the two components, bulge and disc, as a faithful tracer of the stellar mass distribution (M/L in each component does not vary with radius). Then given the estimated intrinsic shape of the bulge and assuming that the disc is a flat system, one may calculate, using the usual Poisson equation, the radial distribution of force (assuming an M/L for each component). This procedure is described in detail in Noordermeer (2006). The observed surface density of neutral hydrogen is included (multiplying by a factor of 1.3 to account for primordial helium), assuming this component to be in a disc with thickness equal to that of the stellar disc.

The Newtonian force $g_{\rm N}$ is then converted into a 'true force', g by using the MOND formula

$$g\mu\left(\frac{g}{a_0}\right) = g_{\rm N}. \qquad (1)$$

Here a_0 is the critical acceleration (the one new parameter of the theory), which we fix at 1×10^{-8} cm s^{-2} (Bottema et al. 2002). μ is the MOND interpolating function which must have the asymptotic dependence $\mu(x) \rightarrow x$ when $x \ll 1$ (the MOND limit) and $\mu(x) \rightarrow 1$ when $x \gg 1$ (the Newtonian limit). Unlike the case of the LSB galaxies, where $|g|/a_0 < 1$ everywhere, in these objects there is a gradual transition from the Newtonian limit in the inner regions to the MOND limit in the outer parts. Therefore, one might expect the form of μ to play some role in the fitted models, at least in the derived M/L values. Two different forms have been considered in the recent literature. Most often one takes

$$\mu(x) = \frac{x}{\sqrt{1+x^2}}, \qquad (2)$$

but more recently Zhao & Famaey (2006) have suggested a simpler form which is consistent with a multifield relativistic extension of MOND (Bekenstein 2004):

$$\mu(x) = \frac{x}{1+x}. \qquad (3)$$

Famaey et al. (2007) have demonstrated that both functions produce reasonable fits to observed rotation curves, but the second (equation 3) generally yields lower M/L values of the visible components. Here we will apply both forms and consider the plausibility of the inferred M/L values as a constraint on μ.

The circular velocity is determined from the true force ($v^2/r = g$) and the M/L values of the two components are adjusted to achieve the optimal fit to the observed curve. Thus, for the objects in this sample, where there is a clear bulge component, there are two free parameters in the fitting procedure. In view of the uncertainties associated with the errors on the observed rotation curves (see previous section), a simple χ^2-minimization does not always result in the best possible fit. Instead, we have used the χ^2-statistics only as a starting point for inspection by eye of the individual fits, and in some cases adjusted the M/L values by hand to achieve a better fit to the overall shape of the rotation curve.

Finally, it should be noted that all distances were taken to be the Hubble law values given by N05 (assuming $h = 0.75$ and corrected for Virgo-centric inflow). Because most of these galaxies are quite distant, Hubble expansion is generally a fair indicator, and distance was not allowed to be an additional free parameter in these fits. However, a few galaxies lie more nearby, in which case the Hubble distance can be off by a considerable amount. In such cases, the quality of the fit might be improved further by allowing the distance to vary within reasonable limits (see also Section 5).

4 RESULTS

The resulting MOND rotation curves are compared to the observed rotation curves in Fig. 1. Here the points with error bars show the observed velocities. The thin, black solid line indicates the Newtonian rotation curve of the bulge component, while the dashed and dotted curves show the contributions of the stellar and gaseous discs, respectively. These Newtonian curves are, in form, those given by Noordermeer (2006). The bold, blue solid curve is the resulting MOND rotation curve assuming the interpolating function given by equation (3). The implied M/L values of the two stellar components are given in Table 2.

The error bars shown here require a word of explanation and a note of caution. There are three sources for the indicated errors.

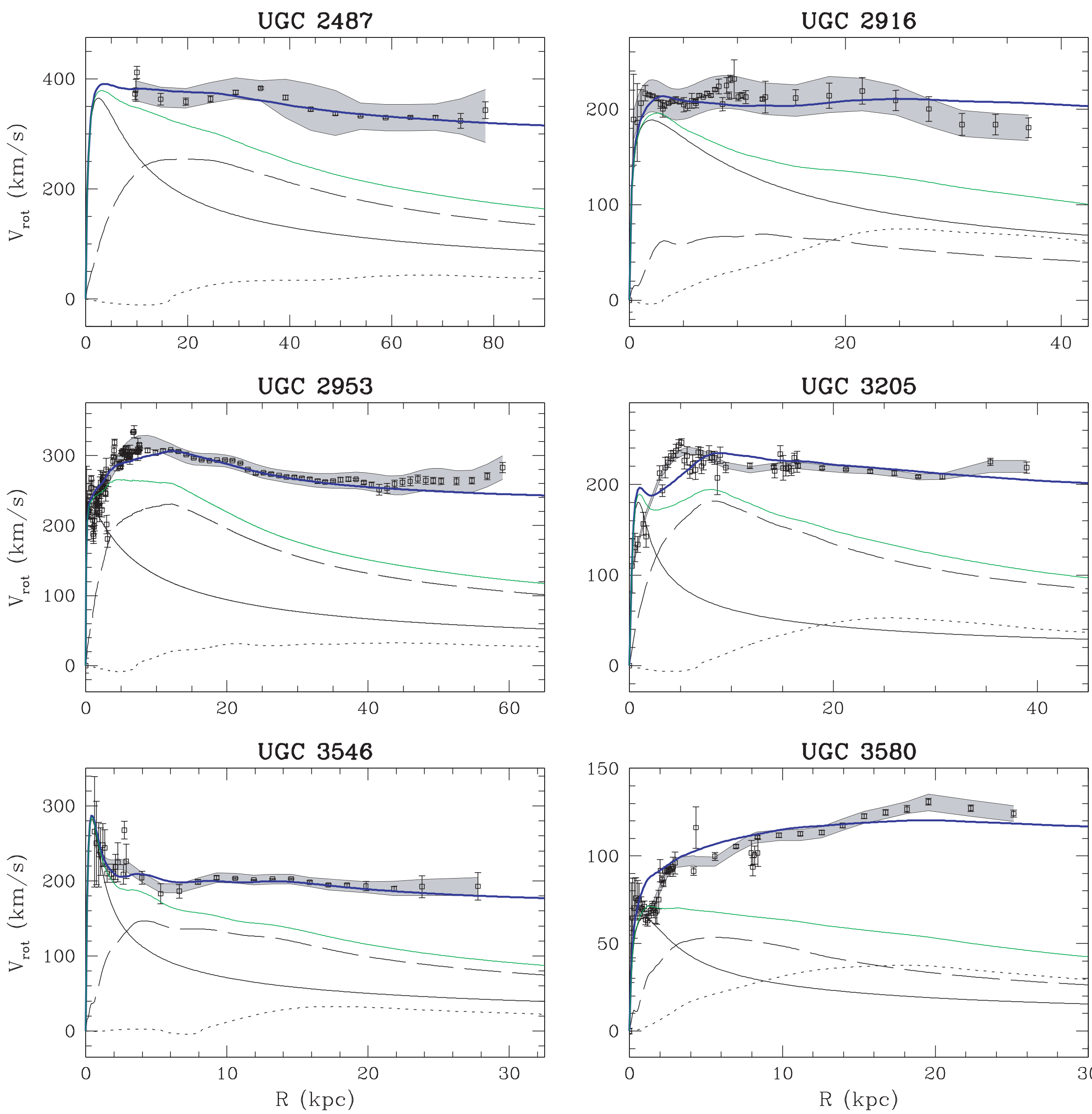

Figure 1. MOND fits to the observed rotation curves of early-type disc galaxies. Data points show the observed rotation curves and error bars give the combined uncertainties due to the measurement errors and kinematical asymmetries. The grey shaded bands give the allowed range due to inclination uncertainties. Thin black solid, dashed and dotted lines give the contributions from stellar bulge, disc and gas, respectively. The thin green (grey) line gives the Newtonian sum of the individual components and the bold blue (grey) lines gives the total MOND rotation curve, assuming the interpolating function μ from equation (3).

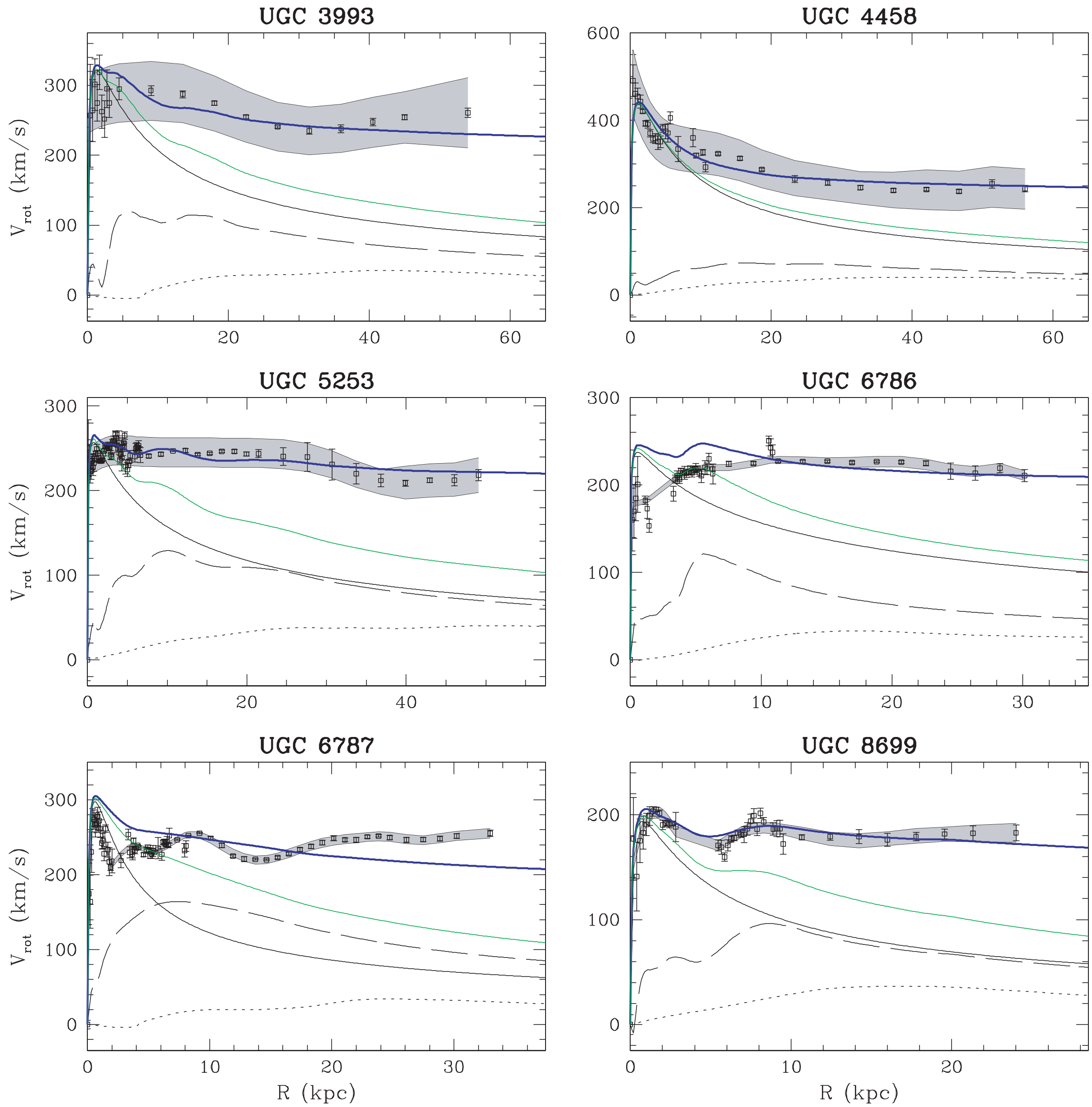

Figure 1 – *continued*

First, there are the formal velocity fitting errors. For the velocities from the optical spectra, these simply come from the derivation of the centre of the emission line. For the velocities from the H I data, they are given by the non-linear least-squares routine that fits tilted rings to the entire two-dimensional velocity fields (Begeman 1987, 1989). In the tilted-ring method it is assumed that deviations from planar circular motion can be modelled as pure rotation in a ring with a different inclination or position angle on the sky. While this may be a fair assumption in the outer regions where warps are often seen, it is most likely not correct in the inner regions where systematic deviations in the velocity field may result from non-circular motion due to a non-axisymmetric gravitational field. In such cases, the formal errors underestimate the true uncertainties.

Secondly, the tilted-ring analysis was performed separately for the approaching and receding sides of the galaxy and this often resulted in different rotation curves for the two different sides. This is also an indication of asymmetries in the velocity fields, but not the sort of bisymmetric asymmetries that would be expected from bar-like distortions. The error on the rotation curve due to these effects is taken to be one-fourth the difference in the rotation curves of the two sides.

Thirdly, there is an error resulting from the uncertainty in the inclination. This was estimated by eye looking at the scatter in the fitted inclination resulting from the tilted-ring program, and is most often the largest contribution to the error budget.

The first two sources of errors were added quadratically to produce the error bars shown in Fig. 1. The latter uncertainty is indicated by the grey shaded bands. Combined, they should be taken as a rough indication of the uncertainty on the derived rotation curve, but, again, they are not true statistical error bars. This means that statistical tests, such as evaluating different models by comparing χ^2 are meaningless and misleading. One should also recall that the

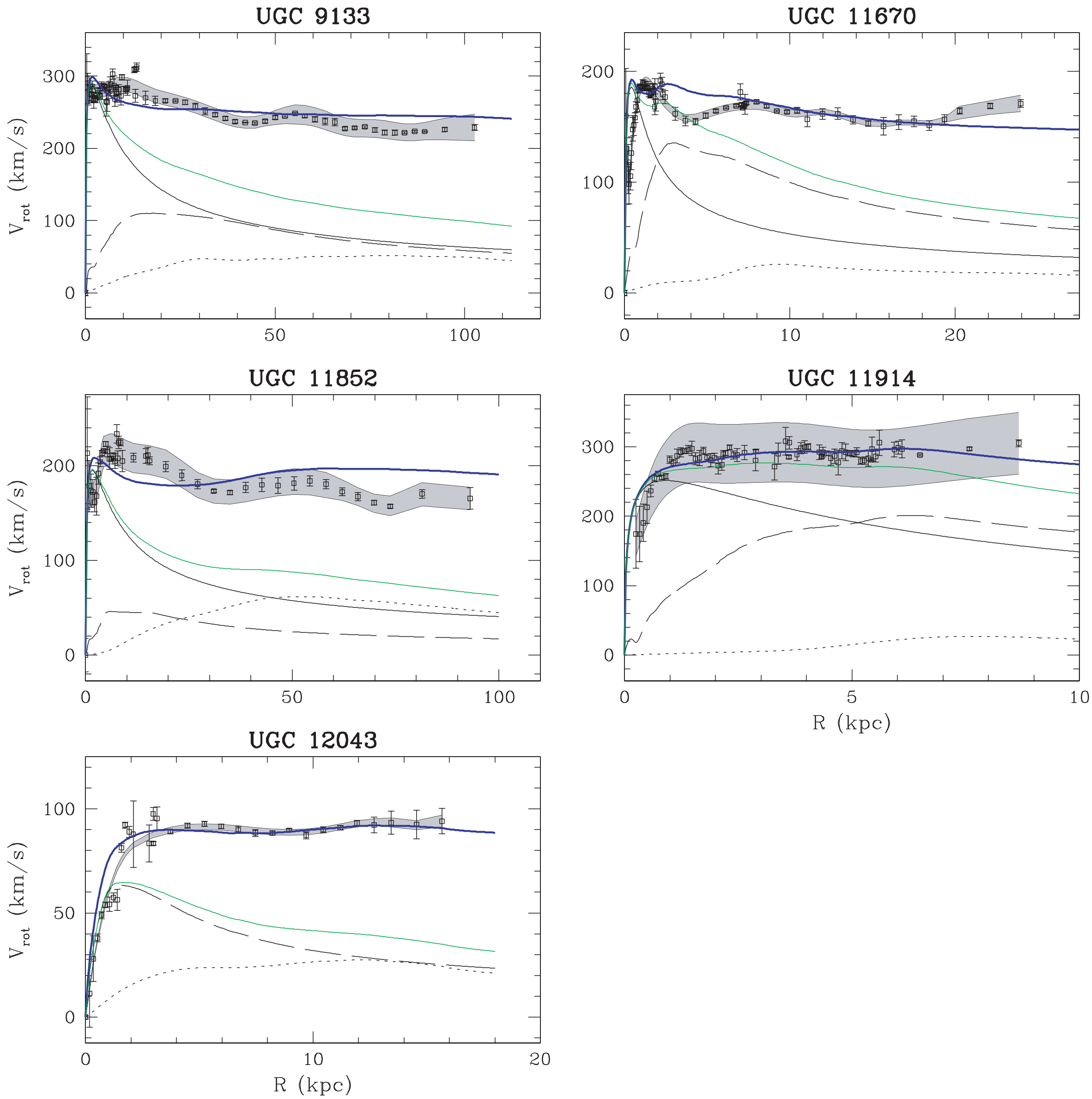

Figure 1 – *continued*

points on the rotation curve are not all independent since the H I velocity field was sampled every half beamwidth of the H I observations.

Fig. 1 shows that many of the observed rotation curves in this sample of galaxies exhibit a rapid rise followed by a gradual decline to a constant asymptotic value (as in e.g. UGCs 2487, 2953, 3993, 4458). This is a fundamental prediction of MOND for galaxies with high central surface brightness systems. Moreover, for these extreme centrally concentrated galaxies, the Newtonian rotation curves generally coincide with the MOND curve for the inner few kpc (i.e. the mass discrepancy in the inner regions is small). This is particularly evident in UGC 11914 where the entire measured rotation curve is in the high-acceleration regime, and, as MOND would predict, the discrepancy between the Newtonian and the observed curve is small.

Considering this sample of rotation curves overall we see that in about 10 out of the 17 cases the MOND rotation curve closely agrees with the observed rotation curve. In some cases (e.g. UGC 2953) the MOND curve is a spectacular reproduction of the observed curve. In five other cases (UGCs 3205, 3580, 6786, 9133 and 11670) MOND correctly predicts the general behaviour of the observed curve but misses details. For two galaxies (UGC 6787, UGC 11852), there are significant differences between the MOND prediction and the observed rotation curve, in the overall shape as well as the details. This is comparable to previous samples (see Sanders & McGaugh 2002) where, in roughly 10 per cent of the cases a substantial mismatch between the MOND predictions and the observed rotation curves was found.

Given the uncertainties in the derivation of rotation curves and their precision as a tracer of the radial force distribution, such an

Table 2. Fitted M/L values in the *R* band for discs and bulges separately, and for the entire galaxies. Columns (2)–(4) refer to the fits with the 'standard' function $\mu(x) = x/\sqrt{1+x^2}$, whereas columns (5)–(7) are for the form suggested by Zhao & Famaey (2006): $\mu(x) = x/(1+x)$.

UGC		Standard μ			μ_{ZF}	
	$(M/L)_d$	$(M/L)_b$	$(M/L)_t$	$(M/L)_d$	$(M/L)_b$	$(M/L)_t$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
2487	6.0	9.0	6.7	4.6	6.5	5.1
2916	3.4	2.6	3.0	1.0	2.5	1.8
2953	5.2	3.9	5.0	3.5	4.5	3.7
3205	4.0	3.6	4.0	2.7	5.0	2.8
3546	4.0	5.9	4.2	2.5	5.9	2.9
3580	4.0	1.0	2.9	2.5	1.5	2.1
3993	26.	6.3	12.2	8.3	8.3	8.3
4458	2.5	7.0	4.6	1.0	6.0	3.4
5253	7.0	4.1	5.2	4.5	3.5	3.9
6786	10.8	4.3	5.6	5.5	6.0	5.9
6787	9.0	5.0	7.4	6.0	5.0	5.6
8699	8.5	4.1	5.9	4.6	4.0	4.2
9133	0.75	4.5	2.3	2.3	3.9	3.0
11670	4.0	3.4	3.9	3.0	3.5	3.1
11852	2.3	5.0	3.3	0.5	5.0	2.1
11914	8.8	6.8	7.9	6.8	6.8	6.8
12043	2.5	–	2.5	2.2	–	2.2

occasional mismatch is not surprising and does not pose an insurmountable problem for MOND. None the less, we discuss these individual problematic cases and the possible sources of the disagreement in the following section.

As is true of late-type galaxies (Famaey et al. 2007), the two different interpolating functions, equations (2) and (3), both provide comparable fits to the observed curves. This is evident in Fig. 2 which shows the MOND and Newtonian rotation curves for UGC 2953 produced by the two different forms. We see that the MOND rotation curves are essentially identical but that the implied masses of the two components are lower in the case of equation (3). Moreover, the relative contributions of the bulge and disc are different in the two cases. The contribution of the bulge, being deep in the Newtonian regime in both cases, is not so dependent upon the form of the interpolating function. But the disc, which extends from the Newtonian to the MOND regime, has a significantly lower implied mass in the case of the Zhao–Famaey interpolating function (equation 3). In general, equation (3) implies a disc with mass less than what has been termed 'the maximum disc' (i.e. the maximum disc mass with a Newtonian rotation curve consistent with that observed in the inner regions).

Overall, the standard interpolating function (equation 2) often requires M/L values which appear implausibly high, in particular for the disc (e.g. UGCs 3993, 6786). This problem is most apparent when the disc M/L values are compared to those of the bulge: in many cases the former is larger than the latter (e.g. 2953, 3993, 5253, 6786), whereas naively, one would expect the redder bulge to have a higher M/L. With the simpler form given by equation (3) however, the fitted M/L values of the disc are lower, and usually comparable to or smaller than the bulge M/L. This indeed suggests that the more gradual transition between Newtonian and MOND dynamics implied by the Zhao–Famaey interpolating function is superior. This was not so noticeable in the later type galaxies considered previously, because the M/L values were generally lower and, most often, only the disc component was present (see however, the results of Bottema et al. 2002, on MOND-implied M/L values for NGC 2841 at the Cepheid-based distance). Most LSB galaxies lie entirely in the MOND regime, so the form of the

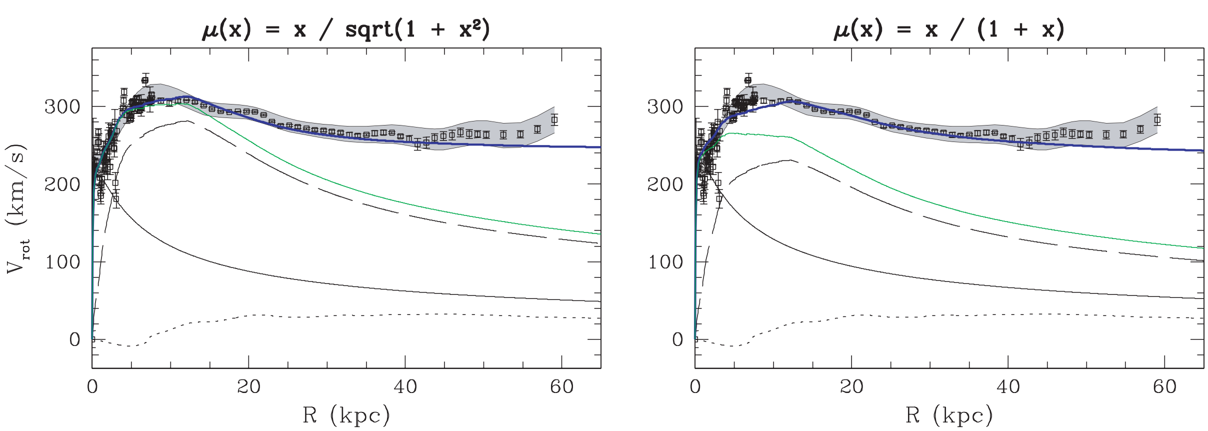

Figure 2. Comparison of the MOND fits to the observed rotation curve of UGC 2953 with the two interpolating functions from equation (2) (left-hand panel) and equation (3) (right-hand panel). Symbols and lines are the same as in Fig. 1.

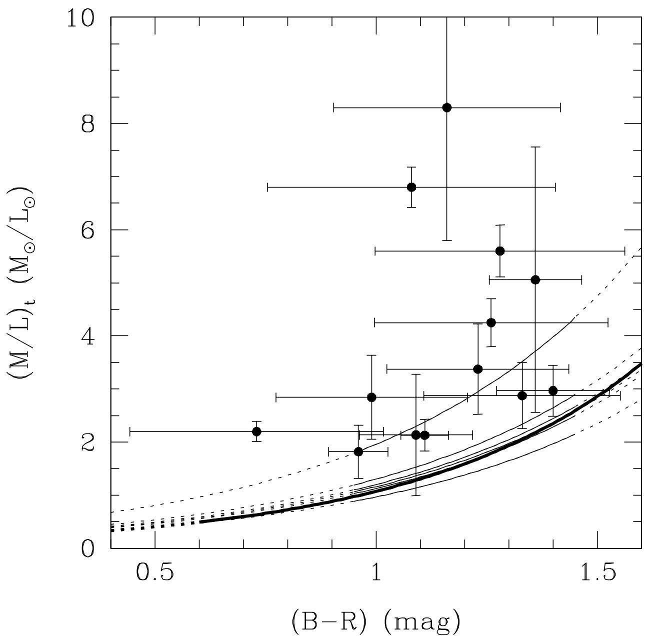

Figure 3. Fitted global (bulge + disc) M/L values in the *R* band versus $B - R$ colour. The data points show the global M/L values for the fits with the interpolating function of Zhao & Famaey (2006, our equation 3). Error bars show the photometric errors and the estimated uncertainties in the derived M/L. The bold line shows the relation derived by Bell & de Jong (2001), while the thin lines show models from Portinari et al. (2004) for different assumptions for the initial stellar mass function. The dashed regions show linear extrapolations beyond their bluest and reddest models.

interpolating function is quite irrelevant; this is one reason why such objects provide such a clear test of MOND in the asymptotic regime. We re-emphasize, however, that with respect to rotation curve fitting alone, there is no reason to prefer equation (3) over equation (2); it is only the plausibility of the relative M/L values for bulge and disc, as well as the generally smaller global M/L, that support the Zhao–Famaey function.

In principle, one could imagine turning the analysis around and using M/L values, for example, as predicted by stellar population synthesis (SPS) models, to empirically constrain the MOND interpolation function. However, given the large intrinsic uncertainties in the SPS models (e.g. initial mass function, star formation history), such a procedure would be premature at this point.

In Fig. 3, we compare the fitted *global* (i.e. bulge + disc) M/L values (with μ given by equation 3) to the predictions of recent population synthesis models of Bell & de Jong (2001) and Portinari, Sommer-Larsen & Tantalo (2004). The values generally scatter above the models, but if we ignore the two highest points (UGC 3993 and UGC 11914), the overall trend is similar – the redder the galaxy, the higher the M/L. It is also of interest that these two discrepant objects have the largest uncertainties in inclination. There is a systematic offset towards higher M/L values than would be predicted by the Bell & de Jong (2001) models, but, as we see in comparison with the Portinari et al. (2004) models, this can be accommodated by adjustments in the initial stellar mass function.

5 INDIVIDUAL OBJECTS

(i) *UGC 3205*. The MOND rotation curve deviates significantly from the observed curve in the inner 10 kpc. This may be a result of streaming motions in the weak bar in this galaxy, which cause the observed velocities to deviate significantly from the local circular velocity and lead to asymmetries in the observed H I velocity field (N05). Outside the region where the velocity field is influenced by the bar, the observed rotation velocities agree well with the MOND predictions.

(ii) *UGC 3580*. The MOND rotation curve is generally similar to the observed curve but the match can be improved considerably by increasing the distance to the galaxy by about 20 per cent. This is within the uncertainty in the distance to this relatively nearby object.

(iii) *UGC 3993*. The overall form of the MOND rotation curve agrees reasonably well with the observed rotation curve; however, the M/L values for the bulge and disc seem unacceptably large with both the Zhao–Famaey interpolating function (>8 for both components) and certainly with the standard function (26 for the disc). Noordermeer (2006) notes that this galaxy deviates strongly from the *R*-band Tully–Fisher relation in the sense of having a luminosity that is too low for its rotation velocity. The galaxy is nearly face-on (assumed inclination of 20°) which means that there is a large uncertainty in the amplitude of the derived rotation curve. This is a plausible source of the anomaly: the galaxy is not underluminous but the amplitude of the rotation curve may have been overestimated due to an inclination overcorrection. If, for example, the actual inclination is between 28° and 30°, which is still within the observational constraints, the asymptotic velocity of this galaxy would be more like 175 km s^{-1} (instead of 250 km s^{-1}) and the global M/L for bulge and disc would be of the order of 2.

(iv) *UGC 6786*. In the MOND rotation curve shown, the M/L values of the bulge and disc have been adjusted to match the decline in the observed rotation curve in the outer regions. In this case, the MOND rotation curve is then too high in the inner regions. There are large side-to-side differences in the inner rotation curve – of about 100 km s^{-1}; such asymmetries complicate the interpretation of the observed radial velocity as a rotation velocity in the inner regions. However, at radii larger than 4 kpc the rotation curve is quite symmetric and the H I and Hα data are consistent. This is an extreme bulge-dominated galaxy; it appears to be more like an elliptical with a small disc rather than a normal Sa.

(v) *UGC 6787*. This object is the most problematic case for MOND in the present sample. The predicted rotation curve differs in form as well as in detail from the observed rotation curve. This galaxy also deviates strongly from the *R*-band Tully–Fisher relation in having a rotation velocity that is too large for its luminosity (Noordermeer 2006). A possible problem here is the distance estimate. This galaxy lies in the direction of the Ursa Major cluster but has a redshift 200 km s^{-1} larger than the high-velocity envelope of this cluster. It is possible that the true distance is larger than assumed here, but that the galaxy has a lower apparent Hubble velocity because of infall into the UMa cluster. However, to achieve reasonable agreement with the MOND rotation curve, the distance must be increased by almost a factor of 2, which seems implausible. An unmodelled warp beyond 16 kpc could cause the apparent rise in the rotation curve, but then the inclination of the gas layer in the outer regions would need to approach 90° (edge-on) to produce the apparent rise of almost 30 km s^{-1}. A combination of plausible distance and inclination corrections would appear to be required to achieve overall agreement. With respect to details, the dip in the rotation curve between 12 and 18 kpc coincides with a change in the fitted position angles, and not the inclinations, of the tilted rings, indicating deviations from simple circular gas motion. This is not a fundamental problem for the fit.

(vi) *UGC 9133*. Although the general form of the MOND rotation curve agrees with the observed curve, the detailed structure is not reproduced well. As in the case of UGC 6787, the fluctuations in the derived rotation curve of this galaxy are coincident with significant fluctuations in the fitted tilted-ring parameters; in particular there is a shift of more than 10° in the position angle of the inclined rings coincident with the bump in the rotation curve at about 60 kpc. Here the tilted-ring program is trying to accommodate a real systematic twist in the two-dimensional velocity field – a twist which may well be due to non-circular motion, in addition to variations in the orientation of the gas disc. In any case, artefacts in the rotation curve which are too dependent upon the tilted-ring fitting program should be interpreted with caution.

(vii) *UGC 11670*. The inner dip in the rotation curve (at about 4 kpc), which is not reproduced by MOND, coincides with a fairly dramatic shift in the fitted position angle of the tilted rings. The true culprit is likely to be non-circular motion in the potential of the bar. The velocity field is rather messy in the outer regions; thus, the observational uncertainties on the outer three points on the rotation curve may be larger than indicated with the error bars. The MOND fit to the rotation curve is considerably improved if the distance is increased by 30 per cent – a possibility because this is the closest galaxy in the sample.

(viii) *UGC 11852*. This galaxy is clearly warped. There is a large shift in the fitted inclination of the tilted rings coinciding with the apparent decline in the rotation curve. Again, it is hard to exclude that possibility that the warp is accompanied by non-circular motions. In fact, N07 reported large residual velocities with respect to the tilted-ring model, indicating that some streaming motions are indeed present. A reasonable fit to this galaxy's rotation curve can also be achieved if it lies at about 75 per cent of its adopted Hubble law distance.

6 CONCLUSIONS

It is rare when an astrophysical hypothesis makes actual predictions in the realm of extragalactic phenomenology and rarer still when those predictions are verified. But with respect to the systematic form of galaxy rotation curves for LSB galaxies, the modified Newtonian dynamics has been exceptional in this respect. Milgrom predicted in 1983, before a substantial population of low LSB galaxies was discovered, that in such objects the rotation curve should rise throughout the visible disc to the final asymptotic value. Since that time, a population of these objects has been discovered and observed, and this behaviour is confirmed.

A supplementary prediction concerned HSB galaxies: in these objects the rotation curve should, after a rapid rise in the very central regions, slowly fall and approach the constant asymptotic value.

The sample presented here offers the chance to test this prediction. These early-type galaxies are mostly of high central surface brightness with a substantial bulge component. The rotation velocities are among the largest observed, ranging up to 500 km s^{-1}. Such galaxies have been previously difficult to observe because of a relatively low and patchy gas content, but with the upgraded Westerbork array and supplementary optical spectroscopic observations in the inner regions, it has become possible to map two-dimensional velocity fields and derive rotation curves that extend well beyond the bright inner regions. The general prediction of MOND with respect to such HSB objects is confirmed.

MOND is now seen to successfully account for the systematics and details of galaxy kinematics from very low rotation, or acceleration, systems (Milgrom & Sanders 2007) to the galaxies presented here with extremely high rotation velocities, *all with the same value of the critical acceleration parameter* a_0. This extends the range of viability of MOND over a range of a factor of 10 in rotation velocity and 10^4 in luminosity/mass. It therefore becomes increasingly problematic to interpret the success of MOND as it merely is an algorithm for explaining the relation between dark and visible matter, as some have suggested. A more natural explanation is to see MOND as a manifestation of a fundamental modification of gravity or inertia in the low-acceleration regime – that MOND is the key to new gravitational physics.

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